Geomorphology and Engineering
Donald R. Coates, Ed. 1976

4

PRECONSTRUCTION TERRAIN EVALUATION FOR THE TRANS-ALASKA PIPELINE PROJECT

Raymond A. Kreig and Richard D. Reger[1]

INTRODUCTION

The route of the Trans-Alaska Pipeline System (TAPS) traverses 789 mi of diverse terrain, including three major mountain ranges and 590 mi of permafrost. Before the pipeline could be designed, detailed information on soil, bedrock, groundwater, permafrost, and other environmental conditions had to be gathered along the entire route and analyzed. Field reconnaissance information and conventional airphoto interpretation were combined with computer-assisted methods in an integrated program designed to evaluate terrain conditions over large areas, where acquisition of ground-truth data is limited by high costs and difficult access.

Airphoto interpretation was used to prepare terrain unit maps on a photomosaic base at a scale of 1:12,000 to show the distribution of landforms in a 2-mi-wide strip along the project route as well as locations of soil borings. This document served as a basis for designing the pipeline and determining construction techniques suitable for each landform along the route. It has also been useful in locating materials sources and disposal sites, establishing oil-spill and erosion-control contingency plans, anticipating avalanche problems, evaluating slope stability conditions, and numerous other applications.

The construction of TAPS at a projected cost of over $6 billion is the largest and most expensive private project in history. Designing and building a 48-in. hot oil pipeline across diverse terrain, including three major mountain ranges (Fig. 1) and 590 mi of permafrost, presented a truly awesome challenge. To comply with stringent government stipulations designed to protect the environment and ensure the integrity of the pipe from hazards such as earthquakes and thawing of ice-rich permafrost, the pipeline route had to be investigated in more detail and with greater accuracy than any previous large construction project in Alaska. Detailed geotechnical information on soil, bedrock, groundwater, permafrost, and other environmental conditions had to be gathered along the entire route, most of which crossed extensive undeveloped and uninhabited areas. Very expensive field operations and difficult access problems led to the development of techniques for evaluating terrain conditions over large areas where ground-truth information is limited.

Investigation of the TAPS route began with the customary compilation of data from the literature and unpublished documents. Because of its importance in mineral investigation, bedrock geology had been mapped by the U.S. Geological Survey on a reconnaissance level or better for most of the route. However, the character of the surficial

[1] The work described in this report was performed while the authors were affiliated with R & M Consultants, Inc., P.O. Box 2630, Fairbanks, Alaska 99707.

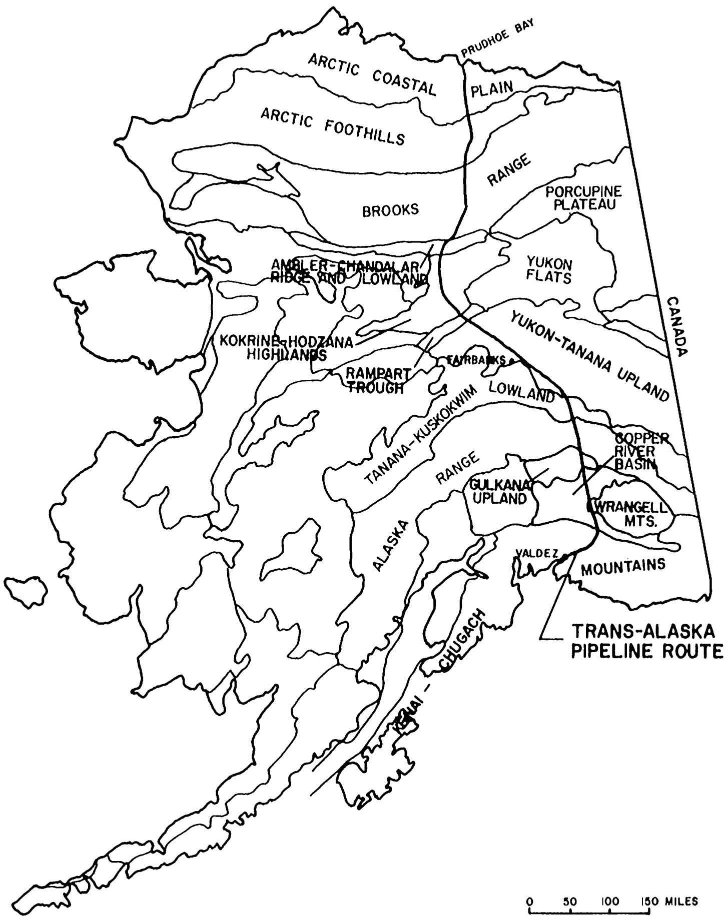


FIGURE 1 *Physiographic provinces in the vicinity of the Trans-Alaska Pipeline route. (Modified from Brew, 1974, Fig. 1.)*

deposits and the distribution of permafrost, which are of primary concern in pipeline design, were largely unmapped and poorly known.

Following a preliminary soil-boring program, in which boreholes were spaced 1 to 10 mi apart, a reconnaissance soil map of the route corridor was prepared at a scale of 1:12,000. A detailed soil-boring program was then undertaken to refine the soil map; define soil properties such as texture, moisture, density, specific gravity, and thaw-settlement characteristics; and provide more detailed information on the distribution of permafrost, groundwater, and bedrock. As of January 1974 over 3,500 soil borings had been drilled along the proposed pipeline route; 2,100 of these were on pipe centerline at an average spacing of 2,000 ft. These borings provided soil test data from over 33,700 samples.

A computer-based data bank was designed for storage and rapid retrieval of the geotechnical information from this extensive sampling and field program. From this massive volume of data, a quantitative assessment of the natural variation of critical soil properties in each landform was summarized by the computer. These summaries have been very useful in comparing conditions in different landforms, establishing exploration priorities, allocating field expenditures, and planning pipeline construction. Timely preparation of construction planning estimates would not have been possible if manual examination of all soil information had been necessary.

Similar techniques have been used to analyze terrain in Australia, Canada, Africa, and Asia.

LANDFORM CLASSIFICATION USED IN THE TAPS PROJECT

In most large construction projects, an intensive soil-boring program is undertaken to determine specific soil properties needed for design. For example, borings are usually spaced about 500 ft apart (or less, in critical areas) along proposed highway alignments Soil properties are then correlated from one boring to the next, and a geologic cross section or series of cross sections is prepared. However, an investigation at this level of detail for the TAPS route was not practical because as many as 20,000 boreholes would have been required during the preconstruction soil investigation of the 789-mi-long alignment. Even this large amount of soil sampling would not have been adequate to delineate completely certain highly variable subsurface conditions found in permafrost terrain. For example, attempts were made during the early soil-sampling program to delineate each occurrence of massive ground ice along the proposed route so that soils potentially subject to excessive differential thaw settlement could be identified. As many as 11 holes were drilled within a 300- by 300-ft area to define a single ground ice mass. It soon became obvious that such detail was prohibitively expensive. Another approach was needed for predicting soil variations without an excessive number of borings in areas where previous knowledge was minimal or generalized, access difficult, and logistics extremely expensive.

The technique of terrain analysis that was ultimately adopted for the TAPS project consisted of identifying landforms by airphoto interpretation and subsequently defining the variation of geotechnical conditions in each landform by field observations and soil borings. The landform approach to terrain analysis is based on the premises that (1) terrain classification by landform is a reliable means of arranging and correlating borehole and soil-test properties, because each landform represents either a single geologic process or a combination of processes that commonly function together; and (2) each landform consequently has a characteristic range of soil properties, such as unified soil classification, dry density, soil moisture, and thaw settlement (Belcher, 1946, 1948). Each ground-truth observation not only provided information about a particular location, but also—when considered with all other observations in the same landform—helped develop a pattern of variation for that landform. Once the variation of properties in each landform was known, an acceptably conservative design for each route segment was developed by identifying landforms through stereoscopic examination of airphotos and the placement of a few strategically located confirmation borings. This system allowed the most efficient use of exploration funds.

A *landform* has been defined by Belcher (1946, 1948) as an element of the landscape that has a definite composition and range of physical and visual characteristics, such as topographic form, drainage pattern, and gully morphology, which occur wherever the landform is found. It should be emphasized, however, that there is no universally accepted standard definition for the term "landform." Some earth scientists and geographers prefer that this term be restricted to the description of topographic features, i.e., mountains, valleys, and basins. But this particular use of "landform" is only of limited value in a geotechnical investigation, because it does not include a consideration of such three-dimensional properties as soil characteristics and other physical and environmental conditions at the surface and at depth. Although the word "form" indicates shape only, it has become generally acceptable to use the term "landform" to describe not only surface topography, but also the deposits comprising the feature (Howard and Spock, 1940).

The landform classification developed for the TAPS project grouped landforms genetically, because similar geologic processes usually result in landforms with similar characteristics and engineering problems. Each landform is identified by letter symbols, the first letter of which is capitalized and indicates the basic genesis of the deposit (e.g., C for colluvium and F for fluvial deposits). Subsequent lowercase letters differentiate specific landforms in each genetic group. These symbols are chosen mnemonically for simplicity and as an aid to users: Fp, floodplain alluvium; Fg, granular fan.

For the specific purposes of the TAPS project, it was necessary to define two supplemental terms more precisely than the general definition of landform given above. A landform consists of one or more single components, called *landform types,* each of which usually represents a single geologic process. Where exposed at the ground surface, the landform type is a morphostratigraphic unit (Gary et al., 1972, p. 464) because it is usually identified primarily by its surface form. Where buried, it is identified by boring information. *Terrain units* are defined as the landform types expected to occur from the ground surface to a depth of about 25 ft. They are used only in map (plan) views to give three-dimensional information on landform types present near the surface of the ground; they are not used in geologic sections. A limiting depth of 25 ft was chosen because deeper soils generally have minimal effect on pipeline design and construction.

Figure 2 illustrates the relationship of terrain units to landform types. In the geologic cross section there are three landform types: floodplain alluvium (Fp), granular alluvial

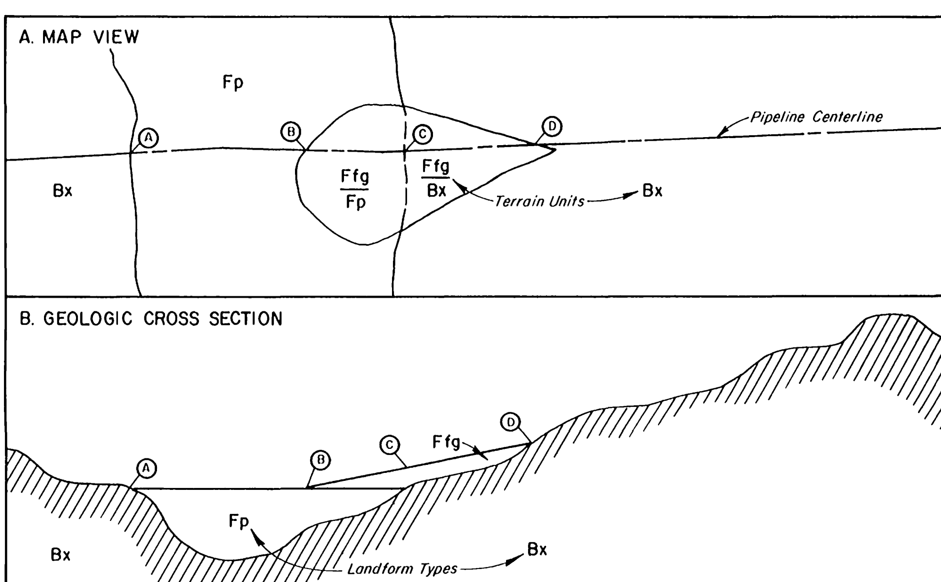


FIGURE 2 *Relationship of terrain units in map view to landform types in geologic cross section.*

TABLE 1 *Landforms Identified Along the Trans-Alaska Pipeline Route*

Symbol	Landform	Symbol	Landform
Bx	Bedrock	Fpb-c	Braided floodplain cover deposits
Bx-u	Unweathered, well-consolidated bedrock	Fpb-r	Braided floodplain riverbed deposits
Bx-w	Weathered or weakly consolidated bedrock	Fpc	Creek or small watercourse deposits
C	Colluvium	Fpm	Meander floodplain deposits
Ca	Avalanche deposits	Fpm-c	Meander floodplain cover deposits
Cg	Rock glacier		
Cl	Slide deposit	Fpm-r	Meander floodplain riverbed deposits
Cm	Mudflow		
Cs	Solifluction deposits	Fpt	Old terrace deposits
Css	Silty solifluction deposits	Fs	Retransported deposits
Ct	Talus	Fss	Retransported silt
Ctc	Talus cone		
Ctp	Protalus rampart	G	Glacial deposits
		Gt	Till sheet
E	Eolian deposits	Gg	Glacier
El	Loess		
Ell	Lowland loess	GF	Glaciofluvial deposits
Elr	Frozen complex upland silt[a]	GFo	Outwash
		GFk	Kames and eskers
Elu	Upland loess		
Elx	Frozen upland loess[b]	H	Man-made deposits
Es	Sand dune deposits	Hf	Fills and embankments
		Ht	Tailings
F	Fluvial deposits		
Fd	Delta deposits	L	Lacustrine deposits
Ff	Alluvial fan	Lt	Thaw-lake deposits
Ffg	Granular alluvial fan		
Fp	Floodplain deposits	M	Marine deposits
Fp-c	Floodplain cover deposits	Mc	Coastal and coastal-plain deposits
Fp-r	Floodplain riverbed deposits		
Fpa	Abandoned floodplain deposits	Mcb	Beach deposits
Fpa-c	Abandoned floodplain cover deposits	Mct	Tidal-flat deposits
Fpb	Braided floodplain deposits	O	Organic deposits
		Ox	Organic basin fillings[a]

[a]On the North Slope only.
[b]In the Yukon-Tanana Upland and Kokrine-Hodzana Highlands.

fan (Ffg), and bedrock (Bx). Between points B and D, a relatively thin granular alluvial fan overlies both bedrock and stream alluvium. This superposition is indicated by terrain unit symbols on the map view between the letters B and C and between C and D. Elsewhere along this geologic section, either floodplain alluvium or bedrock is exposed as a simple landform. Thus, landform types and terrain units are necessary to describe fully and spatially define landforms.

Fifty-five basic landforms were identified along the pipeline route (Table 1). Many landforms commonly occur together in complex relationships and could not be mapped separately; these landforms are represented by composite symbols. An example is the

TABLE 2 *Frequency of Landform Occurrence by Physiographic Province and for Entire Route Based on Cross-sectional Area to Depth of 50 Feet Beneath Pipeline Centerline on Landform-type Profile*

By physiographic province								For entire route		
Physiographic province	Landform	% Area	Cumulative % area	Physiographic province	Landform	% Area	Cumulative % area	Landform	% Area	Cumulative % area
Chugach Mountains	Bx-u	41.2	41.2	Kokrine–Hodzana Highlands	Bx	43.2	43.2	Bx	13.6	13.6
	Ffg	14.5	55.7		C	19.3	62.5	Gt	10.5	24.1
	Bx	12.9	68.6		Bx-w	13.3	75.8	G + L	10.3	34.4
	Gt	11.3	79.9		C or F?	7.1	82.9	Fp-r	9.1	43.5
	Fpb-r	6.1	86.6		Fpt	3.6	86.5	Fpb-r	7.5	51.0
	Fp-r	1.2	87.8		Fs	3.4	89.9	Bx-w	4.8	55.8
					Fp-r	3.3	93.2	Bx-u	3.8	59.6
Copper River Basin	G + L	89.4	89.4		C? or F	1.7	94.9	C	3.2	61.8
	L	2.4	91.8					Ffg	3.2	65.0
	Bx	1.5	98.3	Brooks Range	G + GF	16.1	16.1	G + GF	3.0	68.0
					GF	11.9	28.0	Fss	3.0	71.0
Alaska Range	Gt	35.1	35.1		Fp-r	8.9	36.9	GFo	2.6	73.6
	GFo	14.4	49.5		Bx	6.8	43.7	GF	2.3	75.9
	Bx	10.8	60.3		L	6.5	50.2	Elx	1.7	77.6
	Ffg	7.7	68.0		Fpb-r	5.7	55.9	Fs	1.6	79.2
	Fp-r	6.5	74.5		Ffg	5.4	61.3	L	1.5	80.7
	Fpb-r	6.5	81.0		GF or L	5.4	66.7	Mc	1.2	81.9
	G + L	2.7	83.7		Fs	4.6	71.3	GF or L	0.9	82.8
	Bx-u	1.7	85.4		Gt	3.5	74.8	Es	0.7	83.5
					Bx-u	1.3	76.1	Elr	0.7	84.2
Yukon–Tanana Upland	Bx	22.6	22.6					Fpm-r	0.6	84.8
	Fp-r	17.8	40.4	Arctic Slope	Fpb-r	28.3	28.3	Fp-c	0.6	85.4
	Fss	12.4	52.8		Gt	21.3	50.1	Fpb-c	0.4	85.8
	Elx	7.4	69.0		Fp-r	10.8	60.9	Ht	0.4	86.2
	C	7.2	76.2		Bx-w	7.9	68.8	Fpa-c	0.3	86.5
	Es	2.6	78.8		Mc	7.0	75.8	Fpt	0.3	86.8
	Fpm-r	2.3	81.1		Bx	5.0	80.8	Elu	0.2	87.0
	Fs	1.5	82.6		Elr	4.0	84.8	Ell	0.1	87.1
	Fpc + Cs	1.5	84.1		GFo	2.6	87.4	Ell + Lt	0.1	87.2
	Fp-c	1.5	85.6		Fpb-c	1.6	89.0			
	Ht	1.5	87.1		GF	1.3	90.3			
					Fpa-c	1.1	91.4			

complex glaciolacustrine deposits (symbol G + L) in the Copper River Basin. Although 250 combinations of single landforms were mapped, only 29, representing 87% of the soils along the route, are of major importance (Table 2).

In our terrain analysis, some consideration was also given to different conditions at the ground surface, even though these conditions do not significantly affect the soils at depth. Terraces and dissected remnants of alluvial fans, for example, are flooded infrequently and may have distinctive vegetation and surface characteristics, but these characteristics do not affect the soil properties. Because these types of surface differences do not reflect different soils, they are not ranked at the same level as landform types or terrain units in the classification, but are treated as subordinate *surface phases* of landforms (Table 3). Surface phases are used with terrain units in map views. They are symbolized with lowercase letters in parentheses after the terrain-unit symbols describing the deposits beneath the surface. For example, Fp(ft) designates a relatively young alluvial terrace. In contrast, the alluvium in very old terraces, such as those just north of the Yukon River in the Ray River drainage, is extensively weathered. Because of its altered condition, this ancient, high-level alluvium was not mapped as a surface phase but as old terrace deposits (Fpt).

TERRAIN UNIT MAP AND LANDFORM-TYPE PROFILE

Terrain unit maps were prepared at a scale of 1:12,000 by the interpretation of airphoto and boring information to illustrate geotechnical conditions in a 2-mi-wide zone along the route (Fig. 3). Their main features are (1) a photomosaic showing the areal extent of each terrain unit and the locations of the pipeline alignment, roads, streams, pump stations, and selected borings; and (2) a profile showing the landform types expected to a depth of 50 ft along the pipe centerline. Landform types appear on this profile because boring spacing was generally too great for meaningful correlation of soil types. Also shown on the landform-type profile are groundwater levels, borehole depths and numbers, and permafrost distribution. Other information illustrated includes surface soil classification, a topographic profile, and survey stationing along pipeline centerline.

TABLE 3 *Landform Surface Phases Identified Along the Trans-Alaska Pipeline Route*

Surface phase	Symbol	Topographic condition
Young terraces or dissected remnants	(ft)	Former floodplain or alluvial fan surfaces that are no longer actively flooded. Terrace deposits are not significantly weathered.
Permafrost-modified floodplain	(fk)	A hummocky floodplain surface modified by the formation and/or thawing of permafrost.
Moraine	(gm)	Irregular topography of discontinuous ridges, knolls, and hummocks surrounding closed depressions on till sheets.
Drumlin	(gd)	Low, linear ridges separated by broad, shallow, linear troughs formed in unconsolidated deposits by the flow of glacial ice.

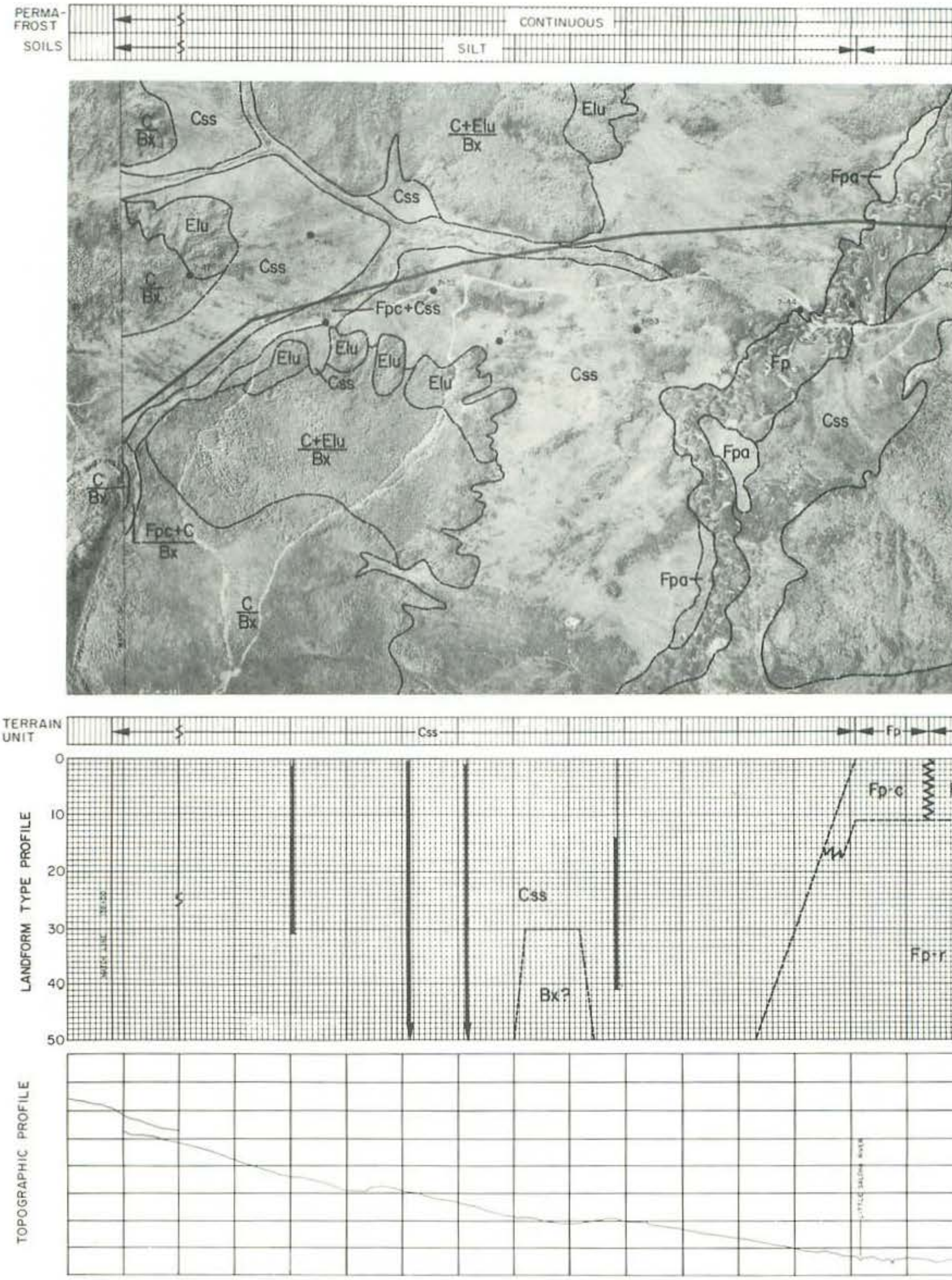
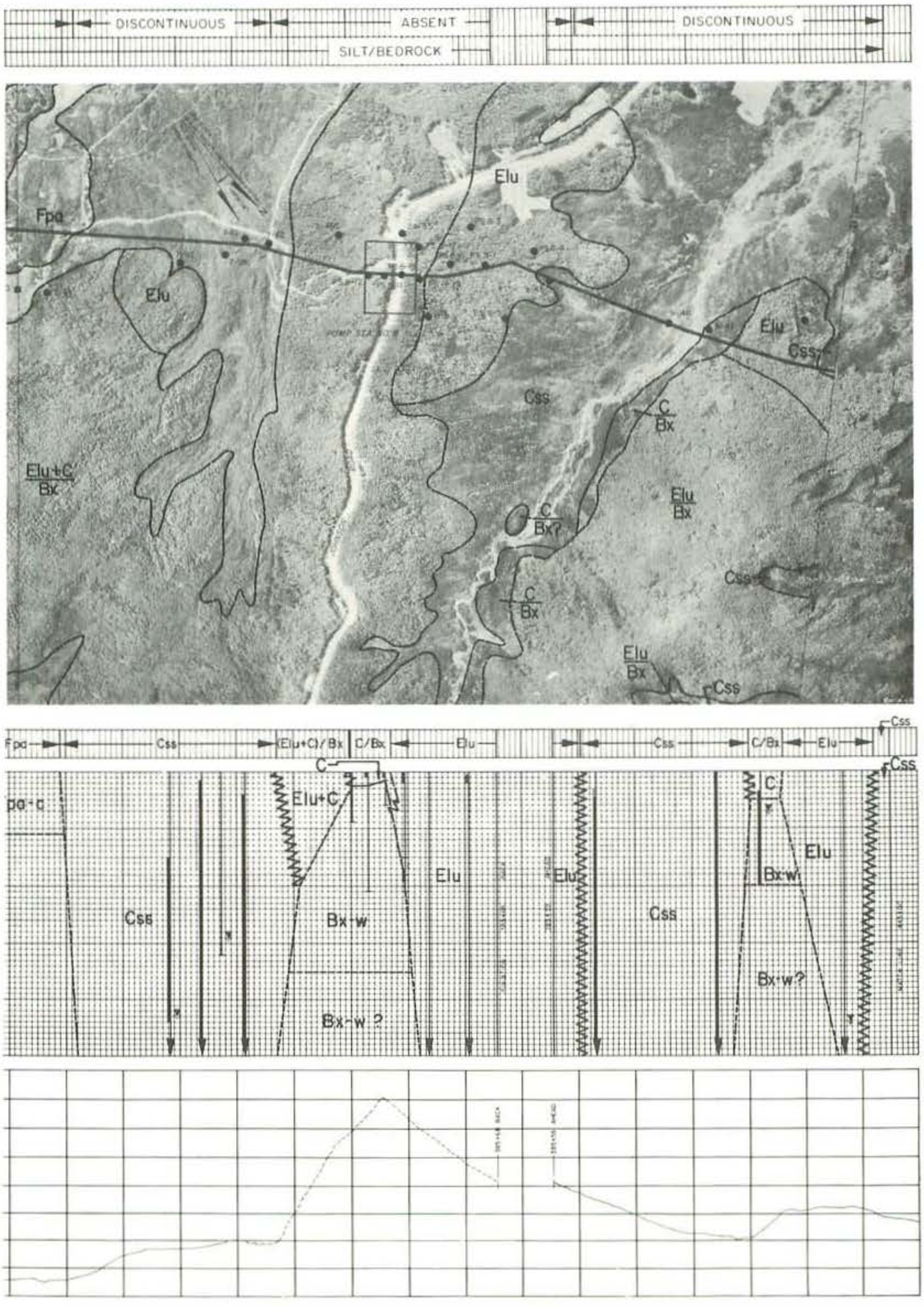


FIGURE 3 *Typical terrain unit map prepared during the preconstruction terrain evaluation of the Trans-Alaska Pipeline route.*



DISCONTINUOUS
ABSENT
DISCONTINUOUS
SILT/BEDROCK
Fpa
Elu
Elu
Elu
Css?
Css
C
Bx
Elu+C
Bx
C
Bx?
Elu
Bx
Css
C
Bx
Elu
Bx
Css
Fpa
Css
(Elu+C)/Bx
C/Bx
Elu
Css
C/Bx
Elu
Css
C
Fpa+c
Elu+C
Css
Bx-w
Bx-w ?
Elu
Elu
Css
C
Elu
Bx-w
Bx-w?
Css

LABORATORY AND SOIL DATA BANKS

A computer-based storage system was set up for geotechnical information from all field investigations and laboratory tests for two reasons: (1) to facilitate report publishing and revision as new information became available, and (2) to facilitate data handling as studies were made of soil property variations in each landform.

Two data banks were created: (1) The *laboratory data bank* (LDB) stored boring location, permafrost conditions, water-table level, and the results of laboratory soil tests, such as gradation and hydrometer analyses, unified soil classification, organic content, specific gravity, dry density, Atterburg limits, and moisture content (Fig. 4). (2) The *soil data bank* (SDB) stored most of the soil-test information on the LDB in addition to all estimated or calculated properties derived from the laboratory results. Calculated properties included dry density, saturation, and moisture content in both frozen and thawed states, excess ice content, thaw strain, and thaw-settlement values (Fig. 5). To prepare a comprehensive thaw-settlement analysis, it was necessary to have actual or estimated soil properties to a projected depth of 99 ft for most borings along the centerline. Therefore, in situ soil properties were estimated for strata intervals that were not actually sampled or tested; for a particular boring, these estimated values are designated by an "E" suffix in the SDB.

Thus, the LDB contains only soil-test results, and the SDB contains both test results and estimated or calculated engineering properties. Both banks contain landform types for all borings and samples. From these two banks a series of summaries were produced to compare conditions in different landforms.

Landform soil property summary tabulates soil test results and estimates of five soil properties for each landform. Moisture content and dry density distributions for specific

```
STATION  1632+59/ 4                 ALYESKA PIPELINE SERVICE COMPANY                              DM-SDB-006
                                             LAB DATA BANK                                          58 -027
PARTY-BORING   9- 66                                                                               07/18/74

**BORING INFORMATION
       ALIGNMENT      OFFSET           DATE    BORING   DIA-      WATER TABLE       BORING
         SHEET                       DRILLED   DEPTH    METER      FT     FT        STATUS
        58 -R 9       F   237        8/01/70    40       2.5      NONE ENCNTRD  SOILS DATA BANK

**LANDFORM TYPES * FP-C             0.0-  4 * FPR  (0)          4 -  8 * FPR                  8 - 40 *

**COBBLES & BOULDERS   XX   0.0-  7.5* SC   7.5- 40.0*

**SOIL STATE * T   0.0-  1.0* F   1.0- 40.0*

**SOIL INDEX PROPERTY DATA                                                         PCT PASSING
       SAMPLE   DEPTH     FROZ-   SOIL     DRY       MOIST    PCT  SPC GR   PCT    SIEVE SIZES  TESTED
         NO    TOP BOT    THAW   CLASS  DENSITY      CONT     SAT   FINE   ORGNC   1    4  200     BY

         2     1.5-  3.0    F     ML       68.2       49.2     90   2.73                100  93    R&M
         4     5.0-  6.5    F                         34.4                                        R&M
         5     6.5-  8.0    F     SM       92.2       26.4     84   2.75                100  24    R&M
         6     8.0-  9.5    F                          8.5                                        R&M
         7    15.0- 16.5    F                         20.6                                        R&M

**SOIL CLASSIFICATION DATA
       SAMPLE   DEPTH     SOIL           PERCENT PASSING SIEVE SIZES            HYDROMETER  ATTER.  WEIGHT
         NO    TOP BOT   CLASS    3   2 3/2   1 3/4 1/2 3/8   4  10  40 200     .02  .002  LL PI    (GM)

         2     1.5- 3.0  ML                                      100  93        31.7       NV NP
         5     6.5- 8.0  SM                                 100  99  98  24      2.5       NV NP




STATION  1632+59/ 4     PARTY-BORING   9- 66                                               58 -027
```

FIGURE 4 *Typical computerized listing of soil index properties stored in the laboratory data bank (LDB).*

FEET FROM VALDEZ 1772337 — ALYESKA PIPELINE SERVICE COMPANY — PAGE 881 OF BOREDATA
ALIGNMENT SHEET 58 REV 9 — LISTING OF VERTICAL PROPERTIES AT EACH BORING — DATE 05/28/74

BORING 9- 66 OFFSET E 237 WATER-TABLE DEPTH 40 BORE-DATE 8/ 1/70 DIAMETER 2.5

SAMP ID	SAMPLE INTERVAL	STRATA INTERVAL	FROZEN D-DEN	FROZEN MOISTURE	FROZEN SAT	EXCESS ICE	STRAIN	THAW SETT	ACC SETT	THAWED D-DEN	THAWED MOISTURE	THAWED SAT	SPEC GRAV	SOIL CLASS
		0.0- 0.4	50.0F	67.0E	84.4	0.00	2.7	0.01	.01	51.4	67.0	88.2	2.20E	OL
		0.4- 1.8	60.0F	58.0E	87.1	12.30	22.6	0.31	.32	77.5	37.4	87.1	2.67E	SP-SM
2	1.8- 3.0	1.8- 3.0	68.2	49.2	89.6	5.24	9.3	0.11	.43	75.2	41.5	89.6	2.73	ML
		3.0- 4.0	75.0E	40.0E	85.8	2.75	7.2	0.07	.50	80.8	36.3	89.6	2.73E	ML
4	5.0- 6.5	4.0- 7.5	82.0F	34.4	87.1	7.46	13.7	0.48	.98	95.0	25.2	87.1	2.73E	SM
5	7.5- 8.0	7.5- 8.0	92.2	26.4	84.3	4.21	8.0	0.04	1.02	100.2	21.8	84.3	2.75	GM
6	8.0- 9.5	8.0-13.0	127.0E	8.5	67.2	0.00	0.0	0.00	1.02	127.0	8.5	67.2	2.74E	GP
7	15.0-16.5	13.0-18.0	107.0E	20.6	94.4	2.40	4.0	0.20	1.22	111.5	18.3	94.4	2.74E	GP-GM
		18.0-23.0	128.0E	10.0E	81.6	0.00	0.0	0.00	1.22	128.0	10.0	81.6	2.74E	GP
		23.0-28.0	138.0E	5.0E	57.3	0.00	0.0	0.00	1.22	138.0	5.0	57.3	2.74E	GP
		28.0-53.0	138.0E	5.0E	57.3	0.00	0.0	0.00	1.22	138.0	5.0	57.3	2.74E	GP
		53.0-99.9	127.0E	10.0E	79.1	0.91	1.8	0.86	2.08	129.3	9.2	79.1	2.74E	GP-GM

BORING - SOIL STATE
T 1.0* F 40.0*

THAW SETTLEMENT SUMMARY
0-8=1.02 * 8-13= * 8-18= .20 * 8-23= .20 * 8-28= .20 * 8-53= .20 * 13-53= .20*

BORING - LANDFORM TYPES
FP-C 4 * FPR (0) 8 * FPR 40 *

BORING - COBBLES & BOULDERS
XX 7.5 * SC 40.0 *

STATION 1632+59/ 4 — ALIGNMENT SHEET 58 REV 9 — BORING 9- 66

FIGURE 5 *Typical listing of measured, calculated, and estimated soil index properties stored in the soil data bank (SDB).*

depth increments are displayed in addition to the percentage of the landform that is frozen. The percentage of samples in each unified soil classification[1] is shown, as well as the amount of massive ground ice encountered and the occurrence of cobbles and boulders (Fig. 6).

Textural triangle plots illustrate the range of soil textures that can be expected within each landform. Because soil textures are defined in terms of four particle sizes (gravel, sand, silt, and clay), and because a triangle plot can show only three variables, it was necessary to use two triangles to represent fully the range of soil samples tested (Fig. 7). The computer program used in developing these triangles extracted gradation and/or hydrometer data from the LDB. The percentages of the clay, silt, and coarse (sand and gravel) fractions were plotted in the left triangle, and the fines (clay and silt), sand, and gravel were plotted in the right triangle.

Modified textural triangle is a graphic display of the range of engineering soil types in each landform (Fig. 8). It is based on the unified soil classification and a textural triangle of the ternary system: gravel-sand-fines (clay and silt). Because the unified soil classification is based entirely on plasticity characteristics when more then 55% of the soil is fines, the upper part of the triangle was replaced by a format showing plasticity-liquid limit relationships and organic content. Data from the LDB are entered on the left side of each box; data from the SDB are entered on the right side and underlined. Soils with 5 to 55% fines are shown in the middle and lower parts of the triangle; they are classified by particle-size gradation and plasticity characteristics of the silt-clay fractions. Soils con-

[1] On the TAPS project, the unified classification system was modified to better define borderline soils by adding additional classifications for soils with 45 to 55% fines.

LANDFORM
G +L

ALYESKA PIPELINE SERVICE COMPANY
LANDFORM SOILS PROPERTY SUMMARY
PROPERTY STATISTICS BY VERTICAL LANDFORM

PAGE 80 OF DM-SDB-008
10/16/74

ALIGNMENT SHEET 12 TO 27 STATION 3+51/ 2 TO 3148+00/ 3 MILEFEET 340514 TO 807255

//////////////////// FROM LAB DATA BANK ////////////////////

MOISTURE CONTENT BY WEIGHT LESS THAN 5	12	15	20	25	30	35	50	C	3C	TOTAL NO. SAMP.	MC AT PCT LESS THAN 5	20	50	80	95	DEPTH OF PROPERTY (FEET)
0	1	4	11	24	40	53	67	88	97	118	15	24	33	68	274	0- 3
0	6	11	15	21	44	58	83	96	99	124	11	23	32	47	64	3- 5
1	9	13	28	45	63	78	94	99	C	325	9	17	26	35	50	5- 8
0	14	22	38	54	68	81	95	C	C	85	9	13	22	34	46	8- 10
1	10	17	33	53	71	80	92	99	C	332	9	16	24	34	62	10- 13
0	15	27	43	62	73	80	93	99	C	350	9	13	21	35	54	13- 18
1	16	33	49	64	76	83	92	99	C	305	9	12	20	33	58	18- 23
0	16	30	50	68	79	88	95	99	C	397	8	12	20	30	49	23- 30
0	12	24	45	66	80	86	94	99	C	828	10	13	21	29	53	30- 50
0	13	23	46	71	83	90	95	98	C	386	9	14	20	27	48	50-100
0	12	23	40	59	73	82	93	98	C	3250	9	14	22	33	57	ALL DEPTH

LESS THAN 25	50	70	80	90	C	+10	20	30	40	NO. SAMP.	LESS THAN 5	20	50	80	95	PROPERTY (FEET)
7	16	37	51	66	92	98	C	C	C	105	16	54	79	95	100	0- 3
1	4	27	40	58	84	92	97	C	C	112	54	66	84	97	114	3- 5
0	1	10	27	47	71	85	93	97	C	286	67	77	91	105	123	5- 8
0	0	5	21	34	57	70	84	95	C	77	68	79	94	115	131	8- 10
0	2	10	18	34	60	81	91	97	C	276	64	81	96	108	126	10- 13
0	2	10	18	34	54	74	87	99	C	280	64	82	98	113	126	13- 18
0	0	9	17	30	48	65	83	98	C	234	68	83	101	118	125	18- 23
0	1	5	13	28	44	62	82	95	99	304	70	86	102	118	129	23- 30
0	2	5	9	27	46	72	89	98	C	611	68	85	101	114	125	30- 50
1	2	5	11	27	49	72	90	99	C	286	70	85	100	115	124	50-100
1	2	9	18	34	55	75	89	98	C	2571	63	81	97	113	125	ALL DEPTH

	TOTAL	BELOW 5 FEET	BELOW 8 FEET
SAMPLES	3278	3028	2701
PCT FROZEN	100	100	100
PCT THAWED			
PCT QUESTIONABLE			

//////////////////// FROM SOILS DATA BANK ////////////////////

MOISTURE CONTENT BY WEIGHT LESS THAN 5	12	15	20	25	30	35	50	C	3C	TOTAL FEET DRILLED	MC AT PCT LESS THAN 5	20	50	80	95
0	10	15	24	36	44	50	60	97	99	327	10	16	34	67	75
1	14	19	39	54	66	75	92	99	C	246	9	15	22	35	67
1	13	21	46	58	69	78	94	99	C	394	10	14	20	35	52
1	15	29	50	65	77	84	95	99	99	268	9	12	19	32	50
1	17	31	52	66	79	86	95	98	99	399	7	12	19	30	49
1	27	42	59	71	81	85	91	99	C	680	8	11	16	29	56
2	23	43	61	70	82	87	91	99	99	679	7	11	16	28	57
1	20	37	59	73	84	90	96	99	C	978	8	12	16	27	47
0	17	30	45	66	80	88	94	99	C	1777	8	12	21	30	52
0	18	30	53	82	89	94	98	C	C	666	8	12	19	24	41
1	18	32	51	67	79	85	92	99	C	6418	8	12	19	30	57

LESS THAN 25	50	70	80	90	C	+10	20	30	40	FEET DRILLED	LESS THAN 5	20	50	80	95
1	10	41	45	56	71	81	93	97	C	325	40	50	81	107	125
0	4	8	22	37	56	75	91	98	99	246	50	79	97	112	124
0	4	7	19	34	52	71	89	98	99	394	64	80	98	115	124
1	3	6	10	23	38	63	83	99	C	268	64	88	104	119	126
1	3	5	10	20	36	61	81	97	C	398	69	89	105	119	127
0	1	10	11	20	35	55	72	96	C	678	65	90	107	123	129
0	1	8	13	22	32	49	73	94	C	671	66	87	110	121	130
0	1	4	9	21	36	54	79	92	99	975	70	89	106	120	132
0	1	5	10	30	50	66	81	93	99	1769	68	85	100	119	132
0	0	2	9	22	51	66	79	90	C	666	76	88	99	120	132
0	2	8	13	27	45	62	80	94	C	6355	62	85	102	119	130

	TOTAL	BELOW 5 FEET	BELOW 8 FEET
FEET DRILLED	6418	5845	5450
PCT FROZEN	100	100	100
PCT THAWED			

*NO OVERSIZE ENCOUNTERED

UNIFIED SOIL CLASSIFICATION	TOTAL	CH	MH-CH	MH	OH	PT	CL	ML-CL	OL	ML	GM-ML	GC-CL	ML-GM
SAMPLES TESTED (PCT)	1211	3.2	1.6	.5	.2	.4	36.8	20.2	.2	14.0		.1	.1
EST FT ENCOUNTERED (PCT)	6335.8	1.5	2.3	.1		.1	26.7	16.6	.6	13.1	.3		

UNIFIED SOIL CLASSIFICATION	CL-GC	GM	GC	GM-GC	GP-GM	GW-GM	GP-GC	GW-GC	GW	GP	SM-ML	SC-CL	ML-SM
SAMPLES TESTED (PCT)	.3	1.3	.1	.3	.2	.1			.4	.2	3.4	1.7	2.7
EST FT ENCOUNTERED (PCT)		3.6	.2	.2	.3				.5	1.1	6.8	1.4	2.8

UNIFIED SOIL CLASSIFICATION	CL-SC	SM	SC	SM-SC	SP-SM	SW-SM	SP-SC	SW-SC	SW	SP	ICE	BX	BX-W
SAMPLES TESTED (PCT)	.8	8.3	.3	.6	1.1	.3				.6			
EST FT ENCOUNTERED (PCT)	.1	16.1	.6	.3	1.9	.1				2.3	.4		

UNIFIED SOIL CLASSIFICATION	OTHERS
SAMPLES TESTED (PCT)	
EST FT ENCOUNTERED (PCT)	

UNIFIED SOIL CLASSIFICATION	ICE+SOIL	BX+SOIL
SAMPLES TESTED (PCT)		
EST FT ENCOUNTERED (PCT)	5.8	

LANDFORM G +L CONSISTS OF G +L *

LANDFORM - G +L

FIGURE 6 *Typical summary of soil index properties extracted from the laboratory data bank (LDB) and soil data bank (SDB).*

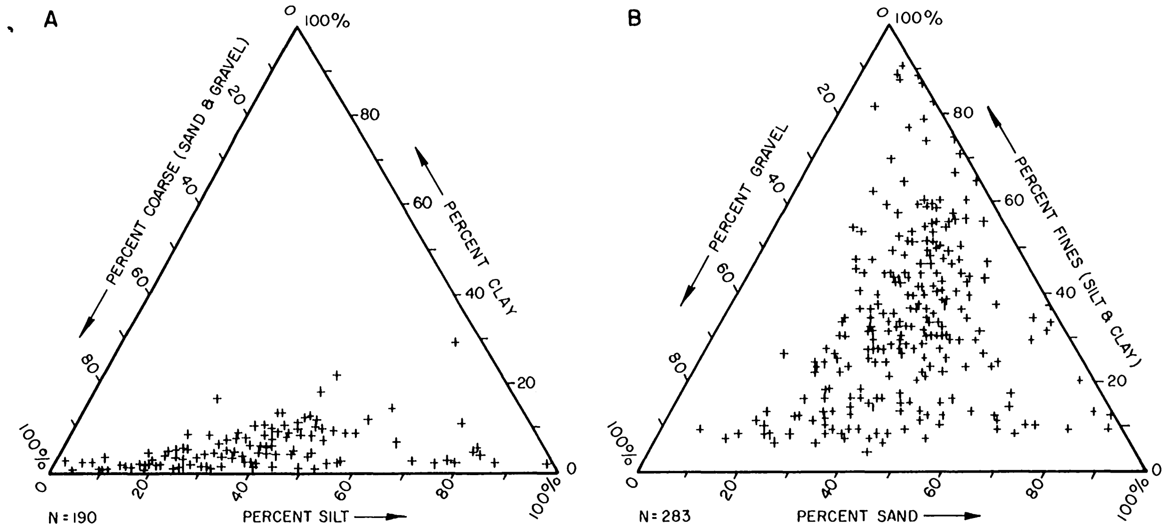


FIGURE 7 *Textural triangle plots of clay-silt-coarse (A) and fines-sand-gravel (B) fractions of glacial till (landform Gt) in the Alaska Range.*

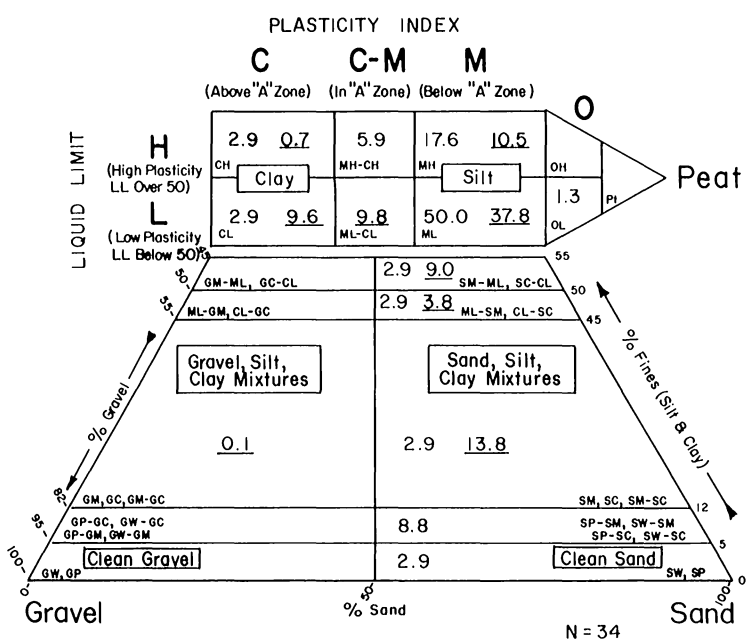


FIGURE 8 *Modified textural triangle showing unified soil classification of lacustrine deposits (landform L) in the northern Brooks Range.*

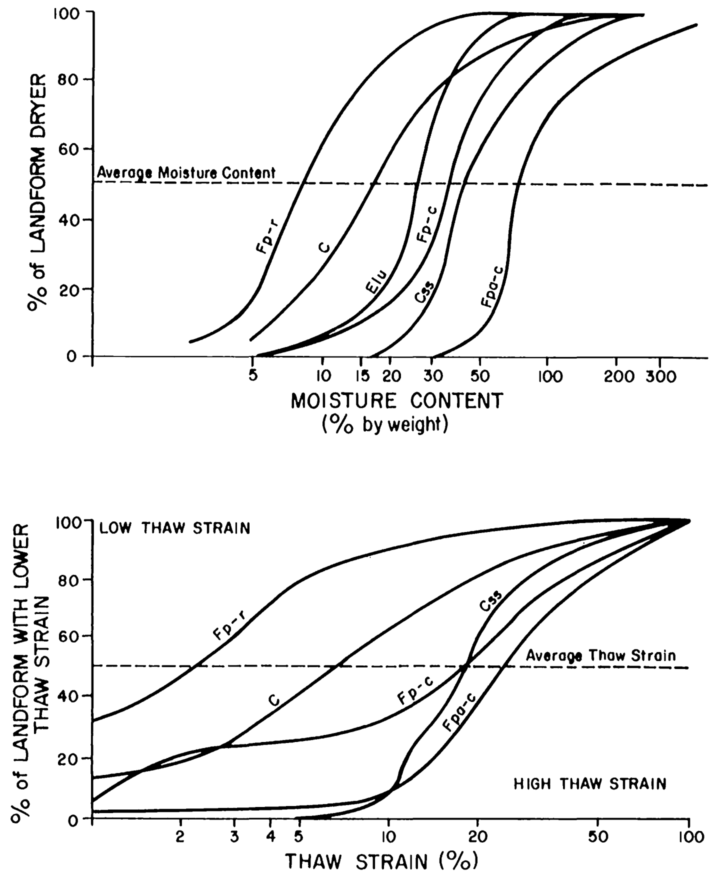


FIGURE 9 *Comparison of moisture-content (upper) and thaw-settlement (lower) curves for various landforms on a typical terrain unit map (Fig. 3).*

taining less than 5% fines are plotted along the base of the triangle and are classified solely on the basis of their size gradations.

Additional summaries of thaw-strain, soil-saturation, and grain-size curves were prepared for each landform. Figure 9 illustrates the differences in moisture-content and thaw-settlement predictions for the landforms on the sample terrain unit map (Fig. 3).

SOIL VARIATION WITHIN LANDFORMS

Landforms may be homogeneous or heterogeneous, depending on the nature of the processes forming them. Homogeneous landforms, such as sand dunes (Es), are usually the result of eolian, fluvial, or lacustrine processes that deposit well-sorted materials. When identified, they define a fairly narrow range of geotechnical characteristics. Heterogeneous landforms contain poorly sorted deposits usually formed by colluvial or glacial processes. The range of soil properties encountered in these landforms often varies considerably. A till sheet (Gt) can contain not only material deposited directly from the melting glacial ice, but also minor amounts of alluvium deposited by streams flowing on or in the glacier, as well as lacustrine deposits laid down in ponds occupying depressions in the stagnant ice.

Variation of landform is best considered within the framework of the physiographic province (Fig. 1). Not only does the pattern of landforms differ significantly in each physiographic province, but our investigation of the TAPS route also demonstrates that the geotechnical properties of landforms may vary from one province to the next because of differences in climate, weathering rates and processes, and predominant bedrock type.

Principles of Landform Variation Analysis

The variation of soil properties within a landform can best be evaluated using data derived from field observations and soil tests of that landform. However, unweighted averaging of such data can be very misleading because of biases incurred through different drilling and sampling methods. When soil properties in a particular landform are studied during an alignment investigation, data should be considered not only from borings drilled along centerline, but also from borings drilled off-line in the same landform. Figure 10 is a hypothetical terrain unit map showing the pipeline route crossing several landforms on a hillside including bedrock (Bx) at the hill crest, colluvium over bedrock [$\frac{C}{Bx}$] on the upper slope, colluvium (C) on the lower slope, and retransported silt (Fss) in the valley bottoms. In this example, the alignment traverses short segments of these landforms, which were sampled by only one or two borings. Within landform Fss there are only two boreholes along centerline, neither of which encountered ice-rich soils. By just considering the results of these two boreholes, one would erroneously conclude that the segment is free of massive ice. On the other hand, if all the borings within landform Fss are considered, whether on or off-line, four out of ten borings encountered ice-rich soils, indicating that about 40% of the retransported silt contains significant ground ice. There is a strong probability that both borings drilled in the short segment of retrans-

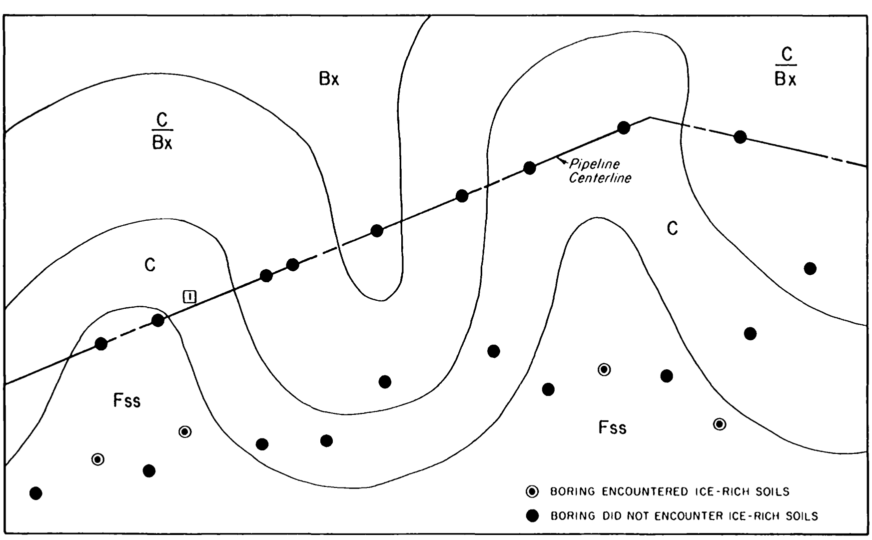


FIGURE 10 *Hypothetical terrain unit map showing distribution of on-line and off-line boreholes encountering different ice conditions in various landforms.*

ported silt could miss the ice-rich sediments. Thus, examination of all available data from local as well as other borings in the same landform provides the most accurate range of expected soil properties.

The use of all available information from borings drilled in a particular landform also provides a reliable basis for predicting soil characteristics in segments of the pipeline route where there are no borings. For example, at locality 1 in Fig. 10, the centerline crosses a short, undrilled colluvial deposit (C). Six borings were drilled in landform C; four are off-line and two are located in a nearby section of the alignment. Soil data from all these borings can provide a reliable basis for predicting the range of characteristics that might be found at locality 1.

Use of Landform Types and Terrain Units in Soil Property Studies

Soil properties and test data generally should only be grouped by landform type, not terrain unit. In Fig. 11, although none of the test pits are sufficiently deep to penetrate the thin glacial till (Gt) and encounter the underlying bedrock (Bx), the terrain unit was classified glacial till over bedrock $[\frac{Gt}{Bx}]$ on the basis of information derived from airphoto interpretation and fieldwork. If the soil properties of the deposits encountered in the test pits in this terrain unit were to be averaged without regard to landform type, the importance of the organic deposits (O) would be overestimated and the presence of bedrock missed completely. These erroneous conclusions would not be reached if a more valid sample of all the landforms present were obtained by deeper drilling. A better method of summing soil properties is by landform type: only the five samples of glacial till should be used to predict properties for landform type Gt, and only the samples from the organic material should be used to predict properties of the organics. When soil properties are summarized by terrain unit rather than by individual landform type, mislead-

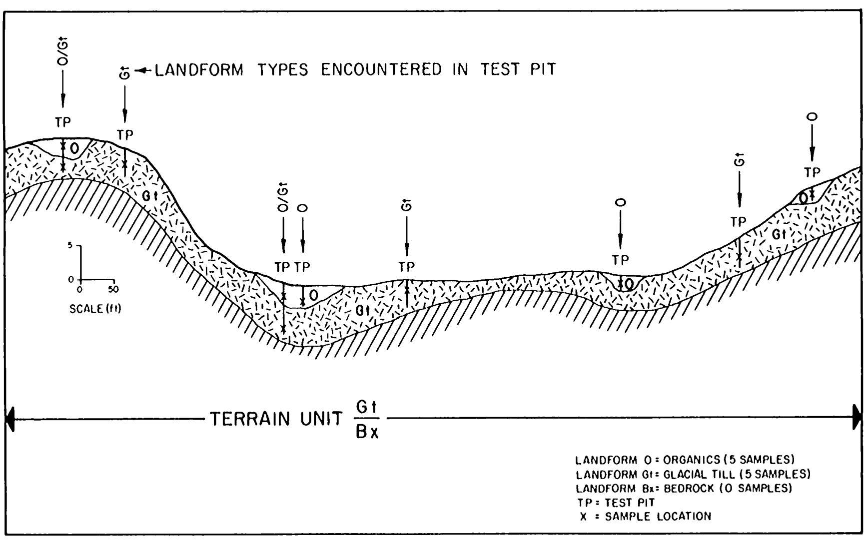


FIGURE 11 *Hypothetical cross section showing relationship of test pits to complex soil conditions in a glaciated terrain.*

ing averages commonly result from the mingling of sample data from dissimilar landforms.

EVALUATION OF METHODS AND DATA

Prediction of Soil Properties

The prediction of subsurface soil properties is generally difficult because these soils are masked by vegetation and surface deposits; furthermore, economic considerations limit the number of borings that can be made to sample them. The number of borings required to evaluate subsurface soil conditions can be considerably reduced if variations in data from subsurface samples can be correlated with visible surface features. Once this correlation is established, reliable estimates of subsurface soil conditions can be made by studying surface patterns.

What is to be done, however, when conditions encountered in boreholes cannot be reliably correlated with surface features or landforms? An example is the erratic and unpredictable occurrence of massive ground ice without distinctive surface expression—a common situation in interior Alaska. The landforms in which massive ice can occur are readily recognized, but the distribution of large ground-ice bodies within these landforms cannot be determined without intensive soil sampling. Another common example is the variability of thaw-settlement values between boreholes without obvious correlation with recognizable surface or geologic patterns. In these situations it is best to consider the *probability* of occurrence within landforms until further research demonstrates a discernible pattern or reason for property variations. Such probabilities should be determined from a random sample population of boreholes or field observations of a recognizable landform.

Weighting Sample Data

The soil-test data used to prepare the landform soil property summaries were generally not collected in a statistically random manner. Biases were introduced in selecting boring locations and in testing the different strata encountered in individual borings; because of these biases, certain soils are often emphasized. A representative determination of soil properties from nonrandom data requires a series of weighting procedures.

Figure 12 illustrates a hypothetical, although typical, situation in a segment of the TAPS route across perennially frozen, retransported silt. Inclusion of all sample data from boring cluster "A," which was drilled to delineate an ice mass, would overemphasize their importance in a landform soil property summary if their significance was not weighted in some fashion. An excellent, although tedious, technique for weighting nonrandom data was used by Thiessen (1911) to evaluate data from irregularly spaced sample locations. Use of this technique considers each boring as representing an area around it defined by lines equidistant between it and surrounding borings (Fig. 13). By weighting boreholes in this manner, the effect of each boring in "A" on the landform soil property summary is minimized.

Another, simpler, technique for minimizing the emphasis of a cluster of borings is to select a single representative boring from the cluster and discard the remaining data. The landform soil property summaries used this method for information derived from the

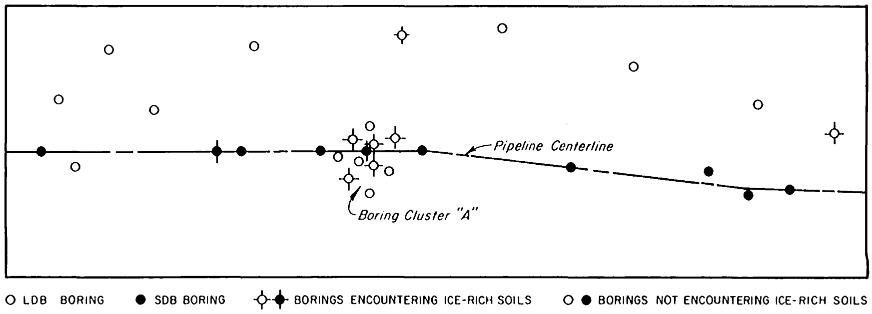


FIGURE 12 *Hypothetical distribution of soil borings in perennially frozen, retransported silt (landform Fss).*

SDB, since only selected representative borings along centerline were included on the SDB.

Sampling bias within an individual test hole can result because in situ samples are difficult to obtain from unfrozen coarse-grained soils. Use of standard penetration samplers in these materials is hindered by frequent refusal and poor recovery; samples for density tests are particularly difficult to obtain. A considerable number of the borings in frozen soils along the TAPS route were drilled with diamond-set core barrels utilizing cooled fluids (Hvorslev and Goode, 1966). This technique is an ideal sampling method because it permits the retrieval of undisturbed cores through all frozen materials. Therefore, when summarizing soil property data in coarse-grained landforms, it is necessary to compensate for variations in drilling and sampling methods.

The SDB contains estimated properties for soil strata not sampled or tested in borings—in addition to strata that were sampled. These properties are weighted according to strata thickness to reduce biases, and appear in the SDB section of the landform soil property summaries (Fig. 6). Soil property information from the LDB is not weighted. The differences between weighted (SDB) and unweighted (LDB) data are illustrated in the density distributions of three landforms (Fig. 14). Dry densities from the two data banks differ significantly only for partly frozen granular alluvium (Fp-r) in the Yukon-Tanana Upland, which was primarily sampled with auger borings. Almost all sampling in frozen granular floodplain alluvium (Fp-r) on the Arctic Slope was accomplished using refriger-

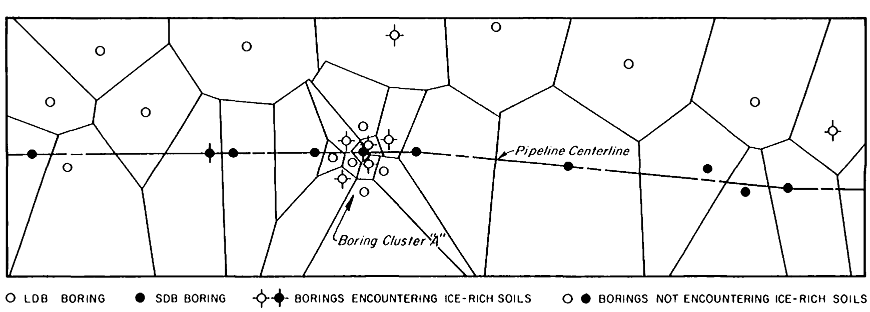


FIGURE 13 *Technique for establishing areas represented by data from individual soil borings.*

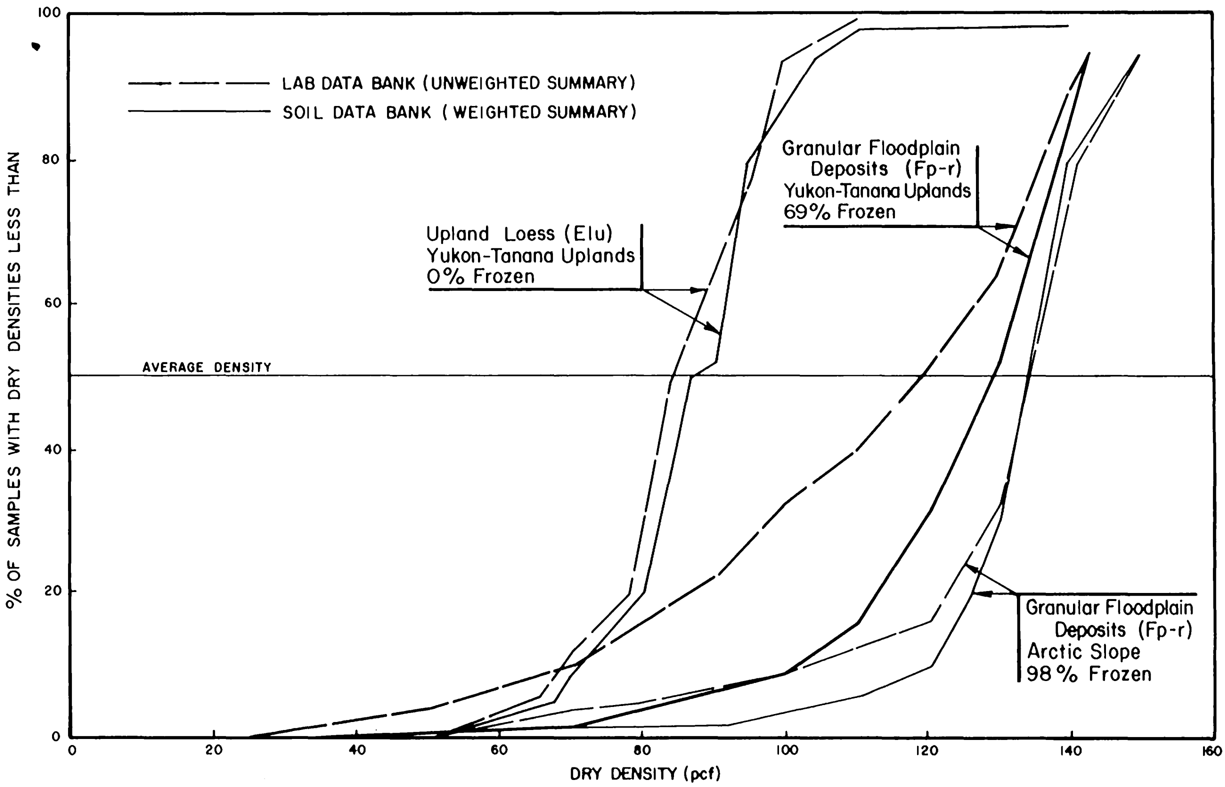


FIGURE 14 *Comparison of weighted (SDB) and unweighted (LDB) dry densities of various landforms in selected physiographic provinces along the trans-Alaska Pipeline route.*

ated coring, and there is little difference between density distributions derived from weighted and unweighted data. The situation is similar in unfrozen upland loess (Elu), where the testing of standard penetration samples provided representative data. Differences between SDB and LDB unified soil classification information are also illustrated by the example of lacustrine deposits (L) in the northern Brooks Range (Fig. 8); these results are due to nonrandom sampling. Most of the borings in this landform were drilled with compressed air methods, and relatively few samples were obtained.

APPLICATIONS OF LANDFORM ANALYSIS

The terrain unit map has served as a design and planning document for construction of TAPS. It was used for evaluating reroute possibilities, locating materials sources and disposal sites, establishing erosion-control and oil-spill contingency plans, anticipating avalanche problems, evaluating slope stability, conducting resistivity studies for establishing cathodic protection procedures, determining work-pad thicknesses, and many other purposes where geotechnical input was required. It was also distributed to contractors for bidding purposes and to government agencies and consultants reviewing the project.

One of the most important applications of the landform approach to the TAPS project was its use in computerized construction planning where input of soil conditions was required. For example, as an aid in materials management, the volume of earthwork was computed for all cuts and fills in each landform. Using soil-texture characteristics and moisture-content data, an estimate was made of excavated material suitable for use as embankments in each landform along the entire route. The landform soil property summaries were very useful for comparing conditions in different landforms, allocating exploration funding and efforts, and estimating ditching and pile-drilling rates so that construction activities could be effectively scheduled and equipment ordered. Timely preparation of these construction planning estimates would not have been possible if manual examination of all soil-boring logs and field data had been required.

COMPARISON WITH OTHER TERRAIN ANALYSIS SYSTEMS

Several other landform classification systems and terrain evaluation methods have been developed to assess terrain over large areas where ground truth is limited or acquisition of data is difficult.

The land resources surveys by CSIRO[1] in Australia (Christian and Stewart, 1968) and the land system atlases published by the MEXE[2] group and Cambridge and Oxford Universities in Great Britain (Beckett et al., 1972) were developed for agricultural land utilization and general-purpose terrain classification. The MEXE system and its derivatives are used in central and southern Africa, Malaysia, and India, and the similar CSIRO system is used in Australia and eastern New Guinea. These systems are based on the recognition of local landform associations, called *land systems,* which are named after a locality in the same fashion that soil series are named by the USDA.[3] However, land systems differ from soil series in that they are in a higher rank of terrain classification generally corresponding to the soil association of the USDA. Unlike the USDA soil series and soil associations, which are defined almost entirely on the basis of pedologic soil characteristics, land systems are defined in terms of all terrain parameters, such as geology, climate, vegetation, and surface morphology, in addition to pedologic soils. The land systems, once defined, are divided into facets or land types that in many cases correspond to individual landforms, such as floodplains or moraines, or minor subdivi-
for agricultural reconnaissance and landuse purposes, was also developed for military uses
Because the land system units are named after geographic localities, the classification does not relate units to one another by genesis. The MEXE system, in addition to being used for agricultural reconnaissance and land-use purposes, was also developed for military uses such as trafficability and engineering construction problems. It was specifically set up for the storage of terrain information in a data-bank system.

In Australia, CSIRO has also developed the PUCE[4] program of terrain evaluation for engineering purposes (Grant, 1973, 1974). This system is based on parent material and geologic age. It has four ranks of subdivisions that allow the classification of terrain down

[1] Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

[2] Military Engineering Experimental Establishment, Christchurch, U.K.

[3] U.S. Department of Agriculture, Soil Conservation Service.

[4] Pattern Unit Component Evaluation.

to very minute components. The units, however, are distinguished by number and not by name. This designation is somewhat inconvenient and confusing to use on a map; however, it is superbly adapted to use with computers. The PUCE system is apparently unrelated to the CSIRO land-system classification.

A terrain classification based on the genesis of landforms is being used in studies of the Mackenzie River valley in Canada (Zoltai and Pettapiece, 1973). Their units are symbolized with letters keyed to geologic processes (such as eolian and fluvial). Other letter symbols indicate landform morphology and surface soil texture. This system is very similar to the system developed for the TAPS project.

All the above systems were designed to classify surface soils for mapping purposes. They are not used in the construction of cross sections or in the grouping of soil data from borings deep enough to encounter buried deposits of different genesis. The landform classification developed for use during the TAPS project required this capability.

SUMMARY

The preconstruction geotechnical investigation of the TAPS route utilized airphoto analysis and landform classification as an aid in correlating geotechnical information from over 3,500 boreholes and numerous field observations. Soil properties in each landform were summarized on two computerized data banks and used for many engineering purposes where geotechnical input was required. The landform approach allowed the timely preparation of construction planning estimates, which, because of the magnitude of the project, would not have been possible using manual procedures.

Several two-dimensional terrain analysis techniques utilizing the landform approach have been developed for different purposes in areas where ground-truth data are scanty and access is difficult. The system of terrain evaluation developed for the TAPS project introduces a three-dimensional concept.

ACKNOWLEDGMENTS

We would like to thank Alyeska Pipeline Service Company for permission to publish this report. Many employees of R & M Consultants, Inc., have contributed to various phases of the terrain evaluation. Although their number is too great to acknowledge them individually, several deserve special recognition, including Robert L. Schraeder, Wendy L. Kline, Lois D. Sala, and John H. Patterson. Comments and criticism of this manuscript by Robert L. Schraeder, Walter T. Phillips, and Wendy L. Kline have been very helpful. The support of Alyeska Pipeline Service Company and R & M Consultants, Inc., is gratefully appreciated.

REFERENCES

Beckett, P. H. T., Webster, R., McNeil, G. M., and Mitchell, C. W. 1972. Terrain evaluation by means of a data bank: *Geog. Jour.*, v. 138, p. 430–456.

Belcher, D. J. 1946. Engineering applications of aerial reconnaissance: *Geol. Soc. America Bull.*, v. 57, p. 727–734.

____. 1948. The engineering significance of landforms: *Highway Res. Board Bull. 13*, p. 929.

Brew, D. A. 1974. Environmental impact analysis: the example of the proposed Trans-Alaska Pipeline: *U.S. Geol. Survey Circ. 695,* 16 p.

Christian, C. S., and Stewart, G. A. 1968. Methodology of integrated surveys: in *Aerial Surveys and Integrated Studies:* Proceedings, UNESCO Conference on Aerial Surveys and Integrated Studies, p. 233–280, UNESCO, Paris.

Gary, M., McAfee, R., Jr., and Wolf, C. L. 1972. *Glossary of Geology:* American Geological Institute, Washington, D.C., 805 p.

Grant, K. 1973. The PUCE programme for terrain evaluation for engineering purposes. I. Principles: *Tech. Paper 15,* Div. Appl. Geomechanics, Commonwealth Sci. and Indust. Res. Organ. of Australia, 32 p.

_____. 1974. The PUCE programme for terrain evaluation for engineering purposes. II. Procedures for terrain classification: *Tech. Paper 19,* Div. Appl. Geomechanics, Commonwealth Sci. and Indust. Res. Organ. of Australia, 68 p.

Howard, A. D., and Spock, L. E. 1940. A classification of landforms: *Jour. Geomorphology,* v. 3, p. 332–345.

Hvorslev, M., and Goode, T. B. 1966. Core drilling in frozen soils: Proceedings, First International Permafrost Conference, *Natl. Acad. Sci–Natl. Res. Council Publ. 1287,* p. 364–371.

Thiessen, A. H. 1911. Precipitation for large areas: *Monthly Weather Rev.,* v. 39, p. 1082–1084.

Zoltai, S. C., and Pettapiece, W. W. 1973. Terrain, vegetation and permafrost relationships in the northern part of the Mackenzie Valley and northern Yukon: *Canada Environmental Social Program for Northern Pipelines, Task Force on Northern Oil Development Rept. 73-4,* 105 p.